

Cosmological science enabled by Planck

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Abstract

Planck will be the first mission to map the entire cosmic microwave background (CMB) sky with mJy sensitivity and resolution better than $10'$. The science enabled by such a mission spans many areas of astrophysics and cosmology. In particular it will lead to a revolution in our understanding of primary and secondary CMB anisotropies, the constraints on many key cosmological parameters will be improved by almost an order of magnitude (to sub-percent levels) and the shape and amplitude of the mass power spectrum at high redshift will be tightly constrained.

1 Introduction

Planck will be the first mission to map the entire cosmic microwave background (CMB) sky with mJy sensitivity and resolution better than $10'$ (1). The science enabled by such a mission spans many areas of astrophysics and cosmology, but in this short proceedings I can focus on only a few. (Further discussion of the cosmological science enabled by *Planck* was covered by Lloyd Knox in his talk at this meeting.) In particular I want to focus on the dramatic revolution *Planck* will represent in the study of primary CMB anisotropies and the universe at $z = 10^3$, with its implications for low- z studies such as those of dark energy. I also want to make a push for a CMB-centric view of structure formation which emphasizes the exquisite constraints on large-scale structure that we already have from the CMB at high- z .

Before I begin with these science topics, it is important to remind ourselves how revolutionary *Planck* will be. In addition to wider frequency coverage (crucial for control of foregrounds) and better sensitivity than *WMAP*, *Planck* has the resolution needed to see into the damping tail of the anisotropy spectrum.

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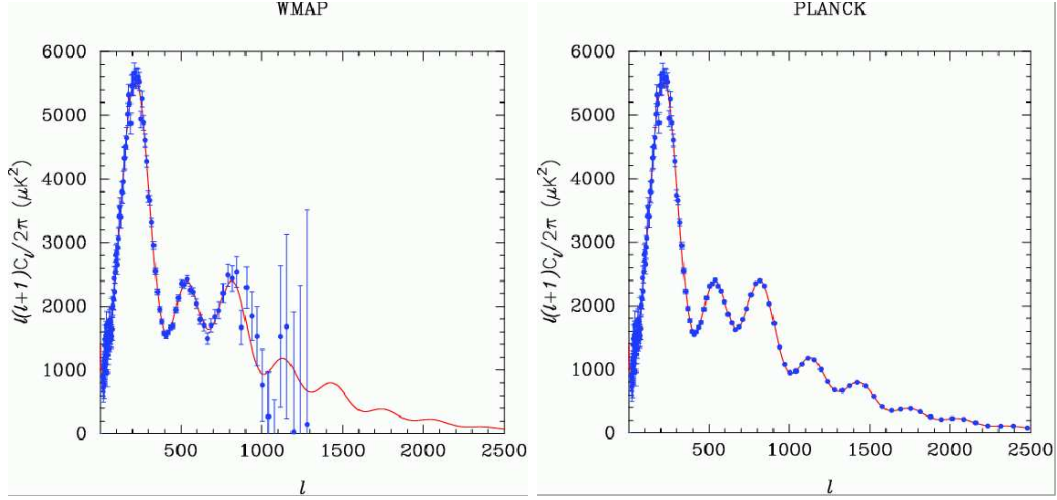


Fig. 1. Forecast measurements of the temperature anisotropy power spectrum from 4 years of *WMAP* or 1 year of *Planck* data assuming nominal sensitivities. We have chosen the same binning scheme to show the advantage that higher resolution and sensitivity confers on *Planck* for high- ℓ science. Figures from (1).

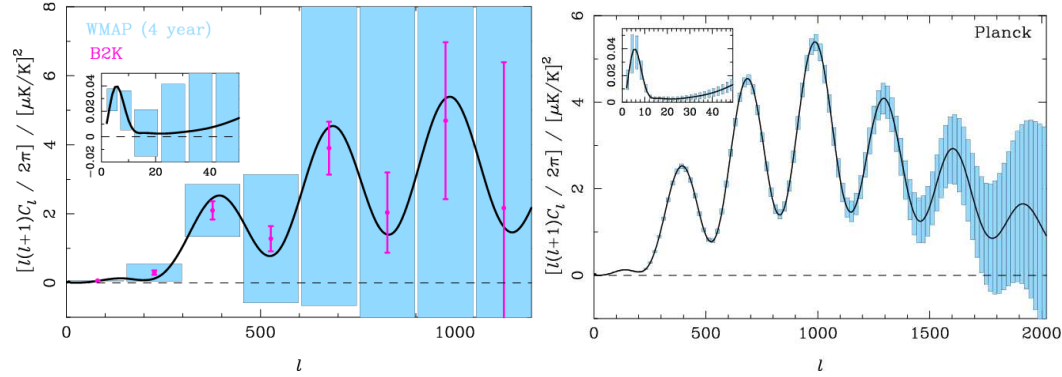


Fig. 2. Forecast measurements of the polarization anisotropy power spectrum from 4 years of *WMAP* or 1 year of *Planck* data assuming nominal sensitivities. One can see clearly the advantage that higher sensitivity confers on *Planck* for polarization science. Figures from (1).

In fact *Planck* will be the first experiment to make an almost cosmic variance limited measurement of the temperature anisotropy spectrum around the 3rd and 4th acoustic peaks.

What does this dramatic increase in our knowledge of the temperature and polarization anisotropy spectra tell us about cosmology, fundamental physics and the formation of structure? Here I will highlight just a few areas where we expect a large impact.

2 The universe at $z = 10^3$ and cosmological parameters

2.1 Constraining cosmological parameters

It is well known that detailed observations of CMB anisotropy, coupled with accurate theoretical predictions, constrain the high redshift universe. The most strongly constrained is the physics which gives rise to the acoustic peaks in the CMB power spectrum, since that is both where the measurements are most accurate and the structure the most rich. To a first approximation the acoustic peaks constrain the physical matter density, $\omega_m \equiv \Omega_m h^2$, the physical baryon density, $\omega_b \equiv \Omega_b h^2$, and an acoustic scale, θ_A or ℓ_A (2). From this we can derive other constraints, for example the distance to last-scattering $D(z = 10^3)$. Currently we know $D(z = 10^3)$ to about 2% (3), with the main source of uncertainty coming not from our knowledge of the peak positions but from the 8% uncertainty in ω_m . This translates into an uncertainty in the expansion rate of the universe near last scattering and hence the distance.

The key to improving our knowledge of ω_m is the higher peaks. *Planck* should determine ω_m to 0.9% (1), almost an order of magnitude improvement over current knowledge. In principle this allows us to determine $D(z = 10^3)$ to 0.2%! This provides an important constraint for cosmological models, e.g. on the dark energy and allows us to calibrate the baryon acoustic oscillation method for measuring $d_A(z)$ and $H(z)$ in the range $z = 0.3 - 3$ (4).

Why are the higher peaks crucial to constraining the matter density? To understand this let us consider how the temperature anisotropies are formed. We know that on small scales the CMB anisotropy spectrum is damped by photon diffusion (5; 6). This process is well understood and essentially independent of the source of the anisotropies. If we remove it we can see the combined effects of the baryon loading and the epoch of equality (Fig. 3).

The baryons give weight to the photon-baryon fluid. This makes it easier to fall into a potential well to become a compression and harder to “bounce” out to become a rarefaction. For adiabatic models the baryon loading thus enhances the compressions (odd peaks) and weakens the rarefactions (even peaks) leading to an alternating sequence of peak heights. Superposed upon this alternation is a general rise in power to small scales – usually obscured by the effects of the exponential Silk damping. The power increase arises because at early times – when the perturbations giving rise to the higher peaks are entering the horizon – the baryon-photon fluid contributes more to the total energy density of the universe than the dark matter. The effects of baryon-photon self-gravity enhance the fluctuations on small scales as follows (7). Since the fluid has pressure it is hard to compress. This makes the infall into

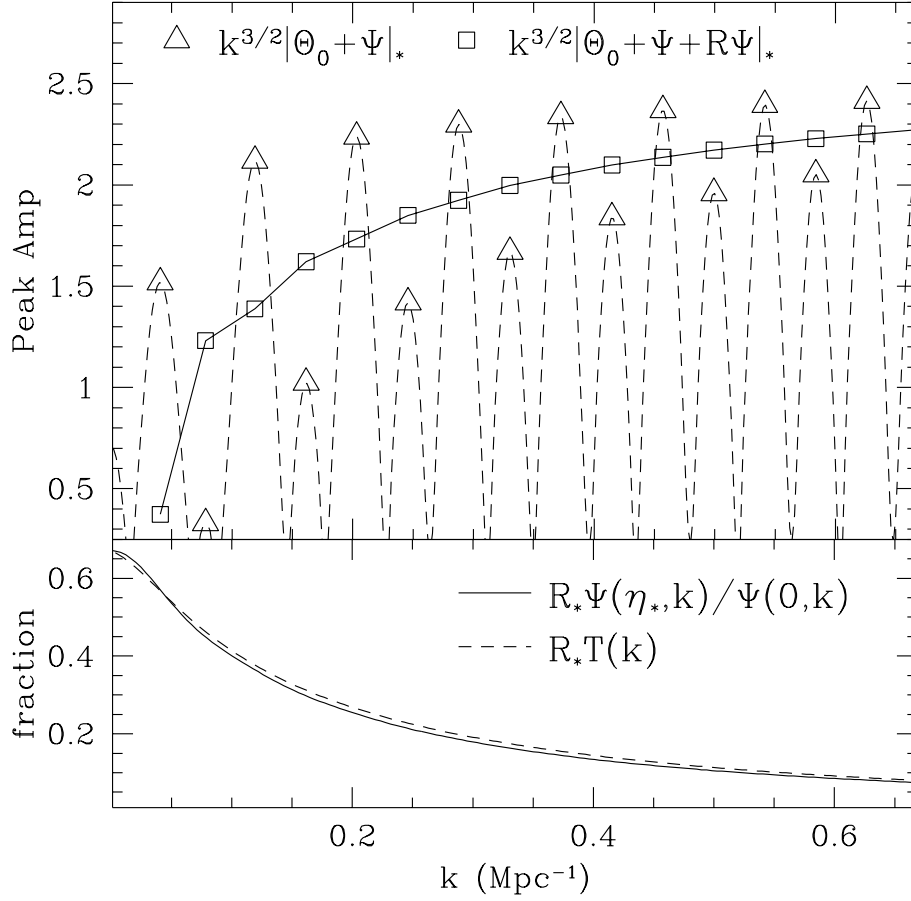


Fig. 3. The temperature anisotropy spectrum with the effects of Silk damping removed. Concentrating on the triangles in the upper panel we see the effects of baryon loading in the modulation of the peaks. If we remove the modulation the boost at high ℓ due to potential decay becomes apparent (squares, see text). The lower panel shows by what fraction the potential has decayed by the present as a function of wavenumber. Figure taken from (6).

the potential wells slower than free-fall, retarding the growth in the overdensity. Because the overdensity cannot grow rapidly enough the potential is forced to decay by the expansion of the universe (see lower panel of Fig. 3). The photons are then left in a compressed state with no need to fight against the potential as they leave – enhancing the small scale power. As the universe expands and larger scales enter the horizon the dark matter potentials become increasingly important and the boost is reduced².

² If we were to ignore the effects of neutrinos near equality and the dark energy at late times the asymptotic value of the excess power would be a factor of 25 compared to the low ℓ plateau. The plateau has an amplitude set by $-\Phi/3$ (8). The infall into the potential well and subsequent decay boosts the power by 2Φ making the small-scale effective temperature perturbation $(2 - 1/3)\Phi = (5/3)\Phi$. In reality

Thus measuring the higher peaks constrains the behavior of the potentials, which respond to the expansion rate of the universe near last scattering. If dark energy is sub-dominant at high z this becomes a constraint on the epoch of equality, z_{eq} , or the matter density. Since it is able to make an almost cosmic variance limited measurement of the higher acoustic peaks, *Planck* provides us with an unparalleled constraint on the (physical) matter density.

2.2 The CMB and dark energy

The nature of the dark energy believed to be causing the accelerated expansion of the universe is one of the most important questions facing cosmology, with implications for our understanding of physics at the deepest levels. For this reason the community has been pursuing dark energy science with a number of different probes. It is sometimes stated that the CMB does not directly constrain dark energy, and this is true. However it is important to point out that almost all of the methods which seek to constrain the dark energy do much better if they include information from the CMB. In fact most analyses include *WMAP* (or projected *Planck*) priors as a matter of course. As a field we have not been particularly effective in promoting the importance of improved CMB anisotropy/polarization measurements for future dark energy experiments, so let me take some time to show one example here: baryon acoustic oscillations.

2.2.1 Acoustic oscillations and the sound horizon

The idea behind the baryonic acoustic oscillation (BAO) method is to make measurements of $d_A(z)$ and $H(z)$ using a calibrated standard ruler which can be measured at a number of redshifts (4). The CMB provides the calibrated ruler through its measurement of the sound horizon:

$$s \equiv \int_0^{t_{\text{rec}}} c_s(1+z)dt = \int_{z_{\text{rec}}}^{\infty} \frac{c_s dz}{H(z)} \quad . \quad (1)$$

The sound horizon is extremely well constrained by the structure of the acoustic peaks. For example from (3) we find $s = 147.8 \pm 2.6 \text{ Mpc} = (4.56 \pm 0.08) \times 10^{24} \text{ m}$. As can be seen from Eq. (1) the sound horizon depends on the expansion history (matter-radiation equality) and the sound speed (baryon-photon ratio). Once s is known and the angular scale of the peaks, θ_A , is measured the distance to last-scattering follows from $s = D\theta_A$. The same physical scale is imprinted upon the matter power spectrum (see Fig. 4), and can serve as a calibrated standard ruler at lower z .

because of the effects of dark energy and neutrinos the effect is more like a factor of 15.

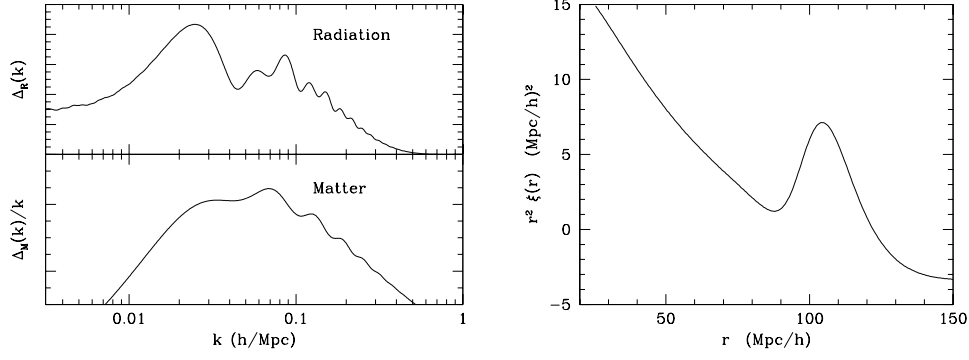


Fig. 4. (Left) The linear theory matter and radiation power spectra vs. wavenumber. The upper panel shows the contribution to the RMS temperature fluctuation per logarithmic interval in wavenumber, and is closely related to the more familiar angular power spectrum plotted vs. angular wave mode ℓ . The lower panel shows the (dimensionless) mass power spectrum (divided by wavenumber k). Note the similar scale of the acoustic oscillations in each spectrum, and the damping to higher wavenumber. (Right) The correlation function, or Fourier transform of the power spectrum plotted in the lower left panel. Note that the almost harmonic series of peaks in Fourier space translates into a single well defined peak in real space with a width of $\mathcal{O}(10\%)$. From (9).

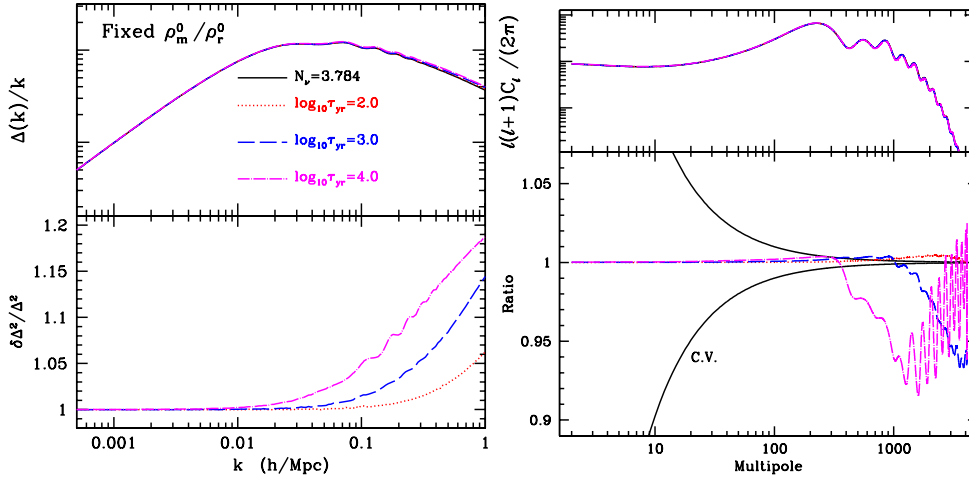


Fig. 5. A plot of the power spectra for decaying neutrino scenarios (see text). The left upper panel shows the (dimensionless) mass power spectrum (divided by wavenumber k) for models which have 10% more matter and radiation than the standard model. The lower left panel shows the ratio of the curves to the $N_\nu = 3.784$ result. The right panels show the radiation spectra for the same models, along with cosmic variance error bars averaged in bins of width $\Delta\ell/\ell = 0.1$.

If we Fourier transform the almost harmonic series of peaks seen in Fig. 4 we predict that the correlation function should have a single well-defined peak at $\sim 100 h^{-1}\text{Mpc}$ (see (10) for a discussion of the physics of the BAO in Fourier and configuration space). This feature has now been seen by several groups (11) in both configuration, $\xi(r)$, and Fourier, $\Delta^2(k)$, space at intermediate

redshift, $z \sim 0.35$. This measurement, along with the CMB, is enough to show the existence of dark energy but larger surveys are needed to constrain its properties.

2.2.2 What could go wrong?

With so much riding on the CMB calibration it is important to ask what could go wrong? Recall the method hinges on the ability to predict s , for which we need z_{rec} , c_s and $H(z)$. It turns out that recombination is very robust, and our current uncertainties in recombination (12) lead to shifts in the sound horizon well below a percent. If we assume the standard radiation content (3 nearly massless neutrino species plus photons) knowing ρ_γ from T_γ gives ω_r . Then knowing z_{eq} is the same as knowing ω_m and $H(z)$. But what if ω_r was different? Could we mistake ν for DE?

It turns out that as long as z_{eq} is still known well from the CMB it doesn't matter! We would misestimate ω_m however in comparing our standard ruler at $z \sim 1$ and $z \sim 10^3$ the same ω_m prefactor enters H^{-1} , d_A and s : each scales as $\omega_m^{-1/2}$. Thus all distance ratios and DE inferences go through unchanged (13). What we do is misestimate the overall scale, and hence H_0 ! It is ironic that we may end up understanding quantum gravity and the mysterious dark energy but still be uncertain about the Hubble constant³.

What about more bizarre histories? As an example imagine a non-relativistic particle of mass m which decays with lifetime τ into massless neutrinos (14). We arrange m and τ so that there is 10% more radiation today than in the standard model, but increase ω_m by 10% so that equality is held fixed. Since it is equality that primarily controls the decay of the potentials at early times the CMB fluctuations look very similar. However, because the universe would be slightly more matter dominated at early times (when the massive particle was a non-negligible contribution to the total energy density) we would expect excess power on small scales, and we can shift the acoustic peaks. Can this lead to a false signature of dark energy?

We show in Fig. 5 the mass and CMB temperature power spectra for a sequence of models with $\log_{10} \tau_{\text{yr}} = 2, 3$ and 4. While one can see subtle shifts in the sound horizon, any model which appreciably shifts s changes the temperature anisotropies at high ℓ enough to be easily seen by *Planck*. Thus while one may not be able to fit the spectrum with a standard model, one would not mistake strange physics at $z \sim 10^3$ for dark energy at $z \sim 0$.

³ I term this the Hubble uncertainty principle.

2.3 Conclusions

To recap the main points of this section, *Planck* will dramatically improve our knowledge of the physical conditions in the universe at $z \sim 10^3$. The physical matter and baryon densities and the distance to last-scattering will be known to sub-percent accuracy. The epoch of equality will be tightly constrained, as will extra species, anisotropic stresses and decaying components at high redshift (13).

3 The CMB prior and structure formation

Already with *WMAP*, and certainly after *Planck*, we will have very precise knowledge of the universe at $z = 10^3$. We will have tightly constrained the densities of matter and baryons, the amplitude of the fluctuations in the linear phase over 3 decades in length scale and the shape of the primordial power spectrum. *Our knowledge of the physical conditions and large-scale structure at $z = 10^3$ will be better than our knowledge of such quantities at $z = 0$.* One should not ignore this dramatic advance in our knowledge – when forecasting the future we should hold the $z = 10^3$ universe “fixed”, not the $z = 0$ one. This is equivalent to imposing strong CMB priors on future measurements.

As an example, knowing ω_m and ω_b allows us to predict the shape of the linear theory (matter) power spectrum extremely accurately over many orders of magnitude in length scale, providing that the lengths are measured in Mpc (or meters) rather than $h^{-1}\text{Mpc}$ as would be more familiar from low- z measurements. Note that knowing ω_m and z_{eq} fixes $H(z)$ at high- z

$$H(z \gg 1) \simeq H_0 \sqrt{\Omega_m(1+z)^3 + \Omega_r(1+z)^4} \propto \omega_m^{1/2} \sqrt{1 + \frac{1+z}{1+z_{\text{eq}}}} \quad . \quad (2)$$

The amplitude of the fluctuations is well constrained by anisotropy measurements, up to a degeneracy with τ — the constrained quantity is roughly $\delta_m e^{-\tau}$. Further, unless dark energy is important at $z \gg 1$, we can evolve the fluctuations reliably from $z \sim 10^3$ to lower z , since $\delta_m \propto a$ for most of the time. In combination this enables us to constrain the high- z matter power spectrum (with lengths measured in *physical* units). For example Fig. 6 shows the range of matter power spectra at $z = 3$ allowed by the *WMAP* 3yr data assuming a standard⁴ ΛCDM model and that dark energy is negligible for $z \geq 3$. The error bars expand slightly at high- k if we additionally allow massive neutrinos,

⁴ We neglect here a possible running of the spectral index, massive neutrinos or a warm dark matter candidate. These will increase the uncertainty on small scales and may be relevant for the formation of the first structures.

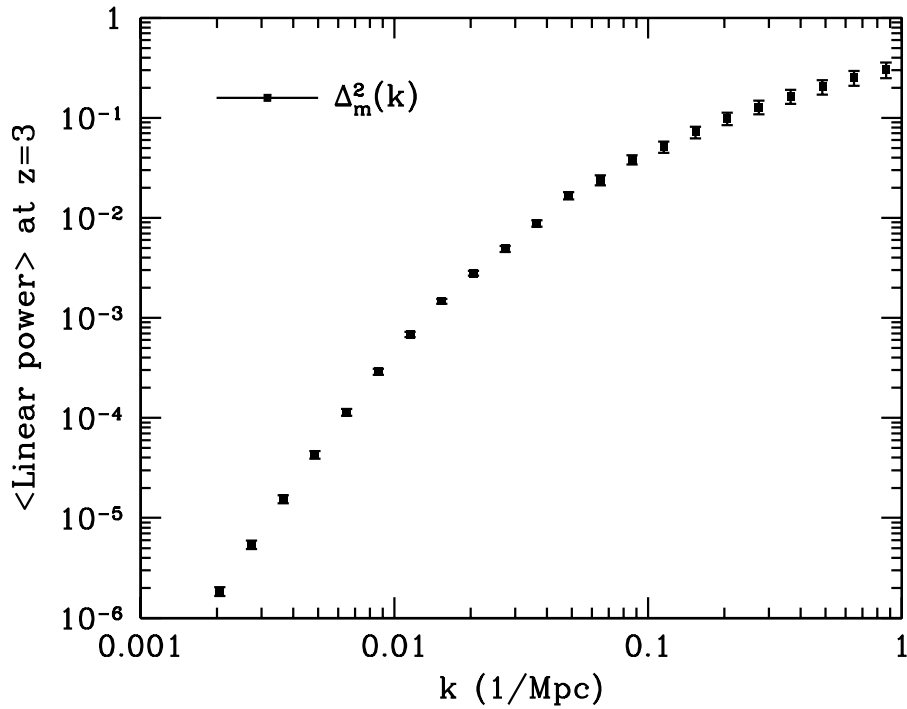


Fig. 6. The range of $\Delta_m^2(k)$ allowed by the WMAP 3yr data assuming a standard CDM model. The data already constrain $\Delta^2(k \simeq 0.01 \text{ Mpc}^{-1})$ to 7%. This drops to 3% if the degeneracy with τ is controlled for.

but near the scales contributing to the first acoustic peak ($k \simeq 10^{-2} \text{ Mpc}^{-1}$) the constraint is already 7% in power. Half of the uncertainty comes from the uncertainty in the optical depth, τ . If we remove that degeneracy the constraint becomes 3% in power or 1.5% in amplitude! We expect this to improve with future *WMAP* data, but with *Planck* the uncertainty will drop to sub-percent levels even with improved modeling of the reionization epoch. Thus in a post-*Planck* world the uncertainty in large-scale structure comes from the extrapolation from $z \sim 3$ to $z = 0$ (which depends on the nature of the dark energy) and the conversion between physical distances and redshift space measures (which depend on h). The former lead to vertical shifts in the spectrum, while the latter give horizontal shifts.

4 Conclusions

Planck will provide a dramatic advance in our knowledge of primary and secondary CMB anisotropies. The constraints on many key cosmological parameters will be dropped to percent, or sub-percent, levels and the shape and amplitude of the mass power spectrum at high redshift will be tightly constrained. Beyond our desire to know the basic parameters of the universe

accurately, and to perform truly precision tests of our cosmological model, the increase in precision will be important for a host of low redshift experiments, including those that aim to constrain the nature of the dark energy.

I would like to thank the organizers of this conference for a pleasant and productive meeting, and Daniel Eisenstein and Wayne Hu for conversations and collaborations upon which some of this work rests. I am grateful to the many members of the *Planck* collaboration who have labored tirelessly to make *Planck* a reality, and especially to Charles Lawrence for his leadership and tireless enthusiasm – and the chocolate donuts. MJW was supported in part by NASA.

References

- [1] The *Planck* collaboration 2005, ESA-SCI(2005)1, available at [www.rssd.esa.int/SA/PLANCK/docs/Bluebook-ESA-SCI\(2005\)1.V2.pdf](http://www.rssd.esa.int/SA/PLANCK/docs/Bluebook-ESA-SCI(2005)1.V2.pdf)
- [2] P.J.E. Peebles, J.T. Yu, ApJ 162, 815 (1970); R.A. Sunyaev, Ya.-B. Zel’dovich, Astrophysics & Space Science 7, 3 (1970); A.G. Doroshkevich, Ya.-B. Zel’dovich, R.A. Sunyaev, Soviet Astronomy 22, 523 (1978).
- [3] D.N. Spergel, et al., submitted to ApJ.
- [4] D.J. Eisenstein, New Astronomy Reviews, 49, 360 (2005).
- [5] J. Silk, ApJ, 151, 459 (1968).
- [6] W. Hu, M. White, ApJ 479, 568 (1997).
- [7] W. Hu, M. White, ApJ 471, 30 (1996).
- [8] R.K. Sachs, A.M. Wolfe, ApJ, 147, 73 (1967); M. White, W. Hu, A&A, 321, 8 (1997).
- [9] M. White, Astroparticle Physics, 24, 334 (2005).
- [10] D.J. Eisenstein, H.-J. Seo, M. White, ApJ in press [astro-ph/0604361]
- [11] D.J. Eisenstein, et al., ApJ, 633, 560 (2005); G. Hütsi, A&A, in press [astro-ph/0505441]; G. Hütsi, preprint [astro-ph/0512201]; N. Padmanabhan et al., preprint [astro-ph/0605302]; C. Blake et al., preprint [astro-ph/0605303].
- [12] P.J.E. Peebles, ApJ, 153, 1 (1968); Ya.-B. Zel’dovich, V.G. Kurt, R.A. Sunyaev, Sov. Phys. JETP, 28, 146 (1969); S. Seager, D. Sasselov, D. Scott, ApJ, 523, L1 (1999).
- [13] D. Eisenstein, M. White, Phys. Rev. D70, 103523 (2004).
- [14] J. Bardeen, J.R. Bond, G. Efstathiou, ApJ, 321, 28 (1987); J.R. Bond, G. Efstathiou, Phys. Lett., B265, 245 (1991); E.J. Chun, H.B. Kim, J.E. Kim, Phys. Rev. Lett., 72, 1956 (1994); M. White, G. Gelmini, J. Silk, Phys. Rev., D51, 2669 (1995); R. Bowen, S.H. Hansen, A. Melchiorri, J. Silk, MNRAS, 334, 760 (2002); E. Pierpaoli, MNRAS, 342, L63 (2003); P. Crotty, J. Lesgourgues, S. Pastor, Phys. Rev., D69, 123007 (2004).